A STUDY OF VACUUM TUBES

AS LOW-POWERED AMPLIFIERS, DESIGNED FOR HIGH EFFICIENCY

A THESIS SUBMITTED FOR THE DEGREE

MASTER OF SCIENCE

IN

ELECTRICAL ENGINEERING

BY

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PREFACE

THIS ANALYSIS OF VACUUM TUBES HAS BEEN BAREFULLY PREPARED BY USING ALL AVAILABLE MATERIAL, NOT TO DUPLICATE ANY PREVIOUS TREATISE, BUT RATHER TO SUPPLEMENT EXISTING THEORIES, AND IF POSSIBLE TO PRESENT A MORE RIGOROUS SOLUTION TO THEORETICAL STUDIES.

THE MATHEMATICAL APPROACH TO THE PROBLEM, ALTHOUGH LOOKED UPON WITH INDIFFERENCE BY SOME DUE TO COMPLEXITIES, IS NEVERTHELESS THE LOGICAL AND ONLY WAY TO ATTACK THE THEORETICAL SUBJECT. VARIOUS PROBLEMS RELATING TO VACUUM TUBES HAVE BEEN SOLVED GRAPHICALLY BY THE POINT-BY-POINT METHOD, WHICH, ALTHOUGH LABORIOUS, IS CONSIDERED THE MOST ACCURATE. REFERENCES AND CHECKS WILL BE MADE TO THIS METHOD FROM TIME TO TIME.

IT IS SINCERELY HOPED THAT THIS WORK WILL BE AN AID TO THE BETTER UNDERSTANDING OF VACUUM TUBE THEORY.

V. A. G.

ATLANTA, GA. 1934

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INTRODUCTION

IN THE ELEMENTARY AS WELL AS THE ADVANCED STUDY OF RADIO THEORY AND PRACTICE THE IMPORTANCE OF A CERTAIN GROUP OF IMPEDANCE ELEMENTS, OR THERMIONIC DEVICES COMMONLY KNOWN AS "VACUUM TUBES", CANNOT BE OVERESTIMATED. THESE UNILATERAL IMPEDANCES FORM THE COUPLING ELEMENT BETWEEN TWO NETWORKS, CONTROLLING, AMPLIFYING, MODULATING OR RECTIFYING THE ENERGY TO BE TRANSFERRED. THE VACUUM TUBE HAS DONE MORE TOWARD THE SENSATIONAL RISE OF RADIO AS AN INDUSTRY THAN ANY OTHER ONE THING. NOT ONLY HAS THE VACUUM TUBE PROVED TO BE THE HEART BOTH OF THE TRANSMITTING AND RECEIVING SETS, BUT VARIOUS MODIFICATIONS ARE FINDING THEIR PLACES IN MANY PHASES OF COMMERCIAL ENTERPRISES. TELEPHONY, ELECTRICAL RECORDING, PUBLIC ADDRESS SYSTEMS, TALKING PICTURES, AND MANY OTHER DIVERSIFIED APPLICATIONS ARE DIRECT PROOF OF THE IMPORTANCE OF VACUUM TUBES.

IN DEFINING A VACUUM TUBE IT WILL SUFFICE TO SAY THAT IT IS AN EVACUATED GAS-TIGHT ENVELOPE IN WHICH ARE PLACED TWO OR MORE ELEMENTS IN CLOSE PROXIMITY TO EACH OTHER. THESE ELEMENTS ARE OF SUCH A NATURE THAT THEY EMIT ELECTRONS, CONTROL THEIR FLOW, OR INTERCEPT THEM FOR CONDUCTION TO THE EXTERNAL CIRCUIT.

THE SIMPLEST TYPE OF VACUUM TUBE CONTAINS ONLY TWO ELEMENTS, A FILAMENT OR CATHODE, AND A PLATE OR ANODE, AND IS VERY APTLY CALLED THE DIODE.

THE DIODE IS SIMPLY A UNILATERAL IMPEDANCE, OR VALVE, PERMITTING CURRENT FLOW IN ONE DIRECTION ONLY. THE MAIN USE OF SUCH DIODES IS RECTIFICATION OF A. C. VOLTAGES.

THE NUMBER OF ELEMENTS WHICH CAN BE CONTAINED IN ONE BULB APPEARS AT PRESENT TO BE ALMOST LIMITLESS. TUBES ARE TERMED DIODES, TRIODES, TETRODES, PENTODES, ETC., ACCORDING TO THE NUMBER OF ELEMENTS RESPECTIVELY. WE ALSO FIND SEVERAL INDEPENDENT UNITS, SUCH AS DIODES, TRIODES, ETC., INCLOSED IN THE SAME BULB, WHICH CAN BE MADE TO WORK INDEPENDENTLY OR IN CONJUNCTION WITH EACH OTHER. THE TRIODE, A THREE ELEMENT TUBE, SEEMS TO BE MORE UNIVERSALLY USED DESPITE THE FACT THAT IT IS OFTEN OVERLOOKED OR APPARENTLY OUTWEIGHTED IN POPULAR ATTENTION BY MANY OF THE MULTI-ELEMENT TUBES. THERE ARE NEVERTHELESS MANY ADVANTAGES WHICH THE SCREEN-GRID TUBE HAS OVER THE TRIODE BECAUSE THE VOLTAGE AMPLIFICATION MAY BE MADE MUCH LARGER; ALSO THE COUPLING BETWEEN OUTPUT AND INPUT CIRCUITS IS VERY MUCH LESSENED WHICH PREVENTS OBJECTIONABLE FEEDBACK. THE TETRODE EMPLOYS AN ADDITIONAL GRID TO ACT AS AN ACCELERATOR OR SPACE-CHARGE GRID WHICH INCREASES THE PLATE RESISTANCE AND THE MUTUAL CONDUCTANCE OF THE TUBE. THE PENTODE HAS FIVE ELEMENTS: THREE GRIDS, A FILAMENT, AND A PLATE. THESE GRIDS ARE RESPECTIVELY, THE CONTROL GRID, THE SPACE-CHARGE OR ACCELERATOR GRID, AND THE SUPRESSOR GRID.

THE LATEST TUBES ARE COMBINATIONS OF THE ONES MENTIONED ABOVE. THESE INCLUDE: DUPLEX-DIODE-PENTODE, A TUBE WHICH HAS TWO DIODE UNITS AND ONE PENTODE UNIT; PENTAGRID CONVERTER, A TUBE WITH FIVE GRIDS WHICH IS USED AS

A MIXER OR FIRST DETECTOR, AN AMPLIFIER, AND AN OSCILLATOR OF A SUPERHETRODYNE RECEIVER.

THE THEORY AS SUBSEQUENTLY DEVELOPED MAY NOT BE RIGIDLY APPLIED TO THE MULTI-ELEMENT TUBES; HOWEVER WITH SLIGHT VARIATIONS, AND ADHERING TO CERTAIN LIMITATIONS, SUCH A PROCEDURE IS PERMISSIBLE. FURTHERMORE A KNOWLEDGE OF THE TRIODE MAY BE USED TO ANALYZE MULTI-ELEMENT TUBES. THUS A TRIODE RETAINS ITS PRESTIGE AS THE MOST UNIVERSAL OF ALL VACUUM TUBES.

HISTORICAL SETTING AND GENERAL CONSIDERATIONS

EXPERIMENTS AS EARLY AS 1873 ARE RECORDED WHICH RELATE TO VACUUM TUBE DEVELOPEMENT. AT THIS TIME F. GUTHRIE OBSERVED THAT A CHARGED ELECTROSCOPE WAS DISCHARGED WHEN A HEATED METAL BALL WAS BROUGHT NEAR IT.

BETWEEN 1883 AND 1889 ELSTER AND GEITEL, GERMAN SCIENTISTS, CONDUCTED OTHER EXPERIMENTS PERTAINING TO THE CONDUCTION OF GASES NEAR HEATED SOLIDS AND FLAMES.

THOMAS A. EDISON IN 1883 WHILE EXPERIMENTING WITH HIS INCANDESCENT LAMP FOUND THAT IF A METAL PLATE WAS SEALED INTO THE GLASS BULB AND THE FILAMENT LIGHTED A CURRENT WOULD FLOW BETWEEN THE FILAMENT AND PLATE. THIS WAS CALLED THE EDISON EFFECT AND WAS THE REAL BEGINNING OF OUR MODERN VACUUM TUBE.

A THEORY GIVEN BY RICHARDSON IN 1903 AND PROVED BY EXPERIMENT SET FORTH THE PRINCIPLE OF ELECTRON EMISSION FROM HOT BODIES. HE FOUND THAT IN EVERY CASE THE RELATION BETWEEN SATURATION CURRENT AND THE TEMPERATURE OF A HOT BODY COULD BE REPRESENTED BY AN EQUATION,

$$I = A\, T^{\frac{1}{2}} \epsilon^{-\frac{B}{T}} \qquad (1)$$

WHERE A AND B ARE CONSTANTS OF THE SUBSTANCE AND T IS THE ABSOLUTE TEMPERATURE. THIS RELATION OF THERMIONIC EMISSION APPLIES NOT ONLY TO PURE METALS BUT ALSO TO CARBON AND HEATED OXIDES. A CURVE SHOWING THIS FUNDAMENTAL RELATION IS REPRESENTED IN FIGURE I.

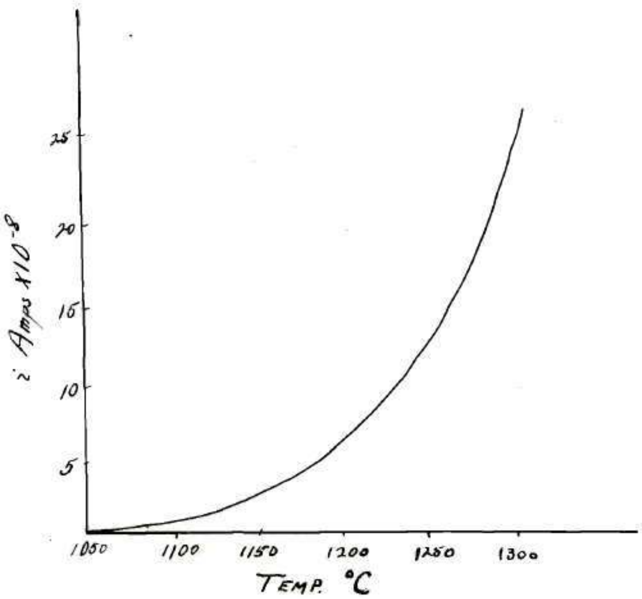


FIG. I

IN LATER EXPERIMENTS LANGMUIR FOUND THAT WHEN A CONSTANT POTENTIAL DIFFERENCE IS MAINTAINED BETWEEN ELECTRODES AND THE TEMPERATURE OF THE FILAMENT OR ELECTRON EMITTER IS GRADUALLY INCREASED THE CURRENT WILL AT FIRST INCREASE IN ACCORDANCE WITH RICHARDSON'S LAW. VERY SOON HOWEVER THE RATE OF INCREASE BECOMES RAPIDLY SMALLER AND A POINT IS REACHED WHERE THE CURRENT CANNOT BE INCREASED REGARDLESS OF THE TEMPERATURE. FIGURE 2 ILLUSTRATES THIS SATURATION CONDITION.

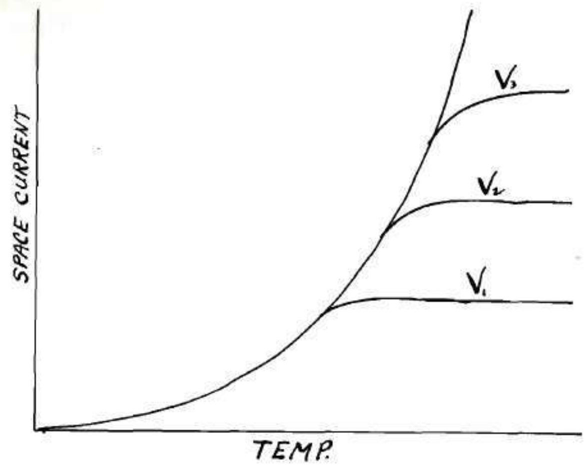


FIG. 2

THIS CONSTANT CURRENT DEPENDS ON THE POTENTIAL DIFFERENCE AND IS REPRESENTED BY THE EQUATION,

$$I = K V^{\frac{3}{2}} \qquad (2)$$

THIS IS KNOWN AS LANGMUIR'S LAW, OR IS SOMETIMES REFERRED TO AS CHILD'S LAW. IN THIS FUNDAMENTAL RELATION OF POTENTIAL DIFFERENCE AND SPACE CURRENT WE HAVE THE FOUNDATION FOR ALL SUBSEQUENT MATERIAL DEALING WITH THE THEORETICAL APPLICATION OF VACUUM TUBES.

THE LAW IS BASED UPON THE ASSUMPTION THAT THE ELECTRONS EMERGE FROM THE FILAMENT WITH NEGLIGIBLE VELOCITY. SINCE IN A MAJORITY OF CASES THIS ASSUMPTION IS ABSOLUTELY VALID, THE TOTAL SPACE CURRENT IS PROPORTIONAL TO THE POTENTIAL DIFFERENCE BETWEEN THE CATHODE AND PLATE RAISED TO THE THREE-HALVES POWER. THE CONSTANT K DEPENDS ON THE GEOMETRICAL DIMENSIONS OF THE TUBE. THERE IS SOME DEVIATION

FROM THIS LAW IN THE CASE OF FILAMENT-TYPE TUBES WHICH IS NOT EXPERIENCED IN HEATER-TYPE TUBES IN THAT THE ELECTRON EMISSION IS ALWAYS PROPORTIONAL TO THE THREE-HALVES POWER OF THE POTENTIAL DIFFERENCE AT THE PARTICULAR PART OF THE FILAMENT IN QUESTION. BUT THERE IS ALWAYS A VOLTAGE DROP IN THE FILAMENT, WHICH CAUSES THE EMISSION TO BE GREATEST AT THE NEGATIVE SIDE OF THE FILAMENT. THIS DEVIATION IS SMALL WHEN RELATIVELY LOW FILAMENT VOLTAGE AND HIGH ANODE OR PLATE VOLTAGE ARE USED. IN LATER EXPERIMENTS WHERE FILAMENT TUBES ARE USED, THE SUPPLY VOLTAGE WILL BE A. C. AND THE ANODE VOLTAGE WILL BE TAKEN RELATIVE TO A CENTER-TAPPED RESISTOR CONNECTED ACROSS THE FILAMENT.

THE MAJORITY OF TUBES NOW ON THE MARKET ARE OF THE THORIATED-TUNGSTEN OR OXIDE-COATED FILAMENT OR CATHODE TYPE. BARIUM AND STRONTIUM OXIDES ARE THE PRINCIPLE OXIDES WHICH ARE USED TO REDUCE THE ELECTRICAL SURFACE TENSION OF THE CATHODE. THEIR USE PERMITS OPERATION OF THE FILAMENT AT LOWER TEMPERATURES AND REDUCES THE CATHODE HEATING POWER.

IN 1904 AND 1905, J. A. FLEMING, AND ENGLISH SCIENTIST, RECOGNIZED THE IMPORTANCE OF THESE DISCOVERIES AND THE POSSIBILITIES OF THE VACUUM TUBE AND EMPLOYED IT AS A DETECTOR OF HIGH-FREQUENCY SIGNALS.

IN 1907, LEE DE FOREST INTRODUCED ANOTHER ELEMENT INTO THE CONVENTIONAL "FLEMING DIODE" AND THE TRIODE BECAME A REALITY.

THE GREATEST PORTION OF THIS PAPER WILL DEAL WITH THE INTRICATE ANALYSIS OF THE TRIODE, WHICH, AS HAS BEEN STATED BEFORE REMAINS PROBABLY THE MOST UNIVERSAL OF ALL TYPES OF VACUUM TUBES. THE THREE ELEMENTS; FILAMENT, PLATE OR ANODE, AND GRID, PERFORM THE FOLLOWING RESPECTIVE FUNCTIONS. THE FILAMENT WHICH IN SOME CASES MAY TAKE THE FORM OF AN INDIRECTLY HEATED CATHODE IS AN EFFICIENT EMITTER OF ELECTRONS. THE PLATE SERVES TO ATTRACT THE ELECTRONS GIVEN OFF BY THE CATHODE AND THE GRID DUE TO ITS SUPERIOR POSITION IS ABLE TO CONTROL THE RATE OF FLOW OF THE ELECTRONS. THESE MINUTE CHARGES OF ELECTRICITY OR ELECTRONS ARE ATTRACTED BY THE POSITIVELY CHARGED PLATE, AND IT IS THEIR MOVEMENT FROM CATHODE TO PLATE THAT CONSTITUTES A FLOW OF CURRENT. ELECTRONS ARE REFERRED TO AS NEGATIVELY CHARGED IONS AND AS FAR AS CAN BE ASCERTAINED HAVE A MASS OF 9×10^{-28} GRAMS EACH.

ALL MATTER IS COMPOSED OF ATOMS AND MOLECULES WHICH IN THEIR NORMAL STATE CONSIST OF POSITIVE NUCLEIS SURROUNDED BY ONE OR MORE ELECTRONS. WHEN THE ATOMS OR MOLECULES ARE DISTURBED EITHER BY THE APPLICATION OF HEAT OR AN ELECTROSTATIC FIELD OR BOTH, THESE ELECTRONS MAY BE DETACHED FROM THEIR PARENT ATOMS, AND IN SUCH A STATE WE HAVE PARTICLES OF NEGATIVE ELECTRICITY WHICH ARE FREE TO MOVE ABOUNT IN SPACE.

THE POSITIVE IONS ARE MUCH MORE MASSIVE AND SLUGGISH THAN THE ELECTRONS SO THAT EVEN THOUGH THEY ADD TO TOTAL SPACE CURRENT, CONDUCTED BY IONIZED GAS, THEIR PROPORTIONATE PART IS VERY SMALL.

THE SPACE SURROUNDING THE FILAMENT AND PLATE IS EVACUATED OF ITS GASEOUS MOLECULES, NOT ONLY TO PREVENT OXIDATION OF THE HEATED FILAMENT, BUT TO PRESENT A PATH FOR THE ELECTRONS WHICH IS RELATIVELY FREE FROM OBSTACLES. HOWEVER, IN SOME CASES A GAS, SUCH AS ARGON OR MERCURY VAPOR, IS INTRODUCED INTO THE TUBE AT LOW PRESSURE AND ADDITIONAL ELECTRONS ARE PRODUCED WHEN THE FAST MOVING ELECTRONS GOING FROM THE HEATED CATHODE TO THE PLATE COLLIDE WITH THE GASEOUS MOLECULES. THIS SCHEME IS EMPLOYED IN THE CONVENTIONAL MERCURY-ARC RECTIFIER, HOT CATHODE MERCURY-VAPOR TUBES, AND MANY SO-CALLED "SOFT TUBES" USED AS DETECTORS IN THE PAST.

ANALYSIS OF A TRIODE

THE THIRD ELEMENT OR GRID OF THE TRIODE WAS INTRODUCED TO CONTROL THE FLOW OF ELECTRONS FROM CATHODE TO PLATE, AND IT WAS THIS STEP WHICH LED TO THE GREATEST PROGRESS THAT HAS BEEN MADE IN RADIO DEVELOPEMENT. THE GRID IS A SCREEN-LIKE ELECTRODE SITUATED BETWEEN CATHODE AND PLATE. IT IS NORMALLY OPERATED AT A NEGATIVE POTENTIAL WITH RESPECT TO THE CATHODE, SO THAT IT DOES NOT ATTRACT BUT RATHER REPELS THE ELECTRONS GIVEN OFF BY THE CATHODE. THE ELECTROSTATIC FIELD PRODUCED BY THE GRID THUS SERVES AS A CONTROL VALVE REGULATING THE NUMBER OF ELECTRONS THAT ULTIMATELY REACH THE PLATE.

THE CURRENT THAT WILL FLOW FROM CATHODE TO PLATE WILL DEPEND ON THE VOLTAGES APPLIED TO THE GRID AND TO THE PLATE. IF THIS CHALLENGES THE MIND OF ANY WHO HAVE NORMALLY COME TO THINK OF A CURRENT FLOW IN THE CONVENTIONAL SENSE, FROM POSITIVE TO NEGATIVE TERMINAL, IT MIGHT BE STATED THAT THIS DIRECTION IS PURELY CONVENTIONAL AND I HAVE CHOSEN TO SPEAK OF CURRENT FLOW IN THE SAME DIRECTION AS THE MOVEMENT OF THE ELECTRONS.

IN A TRIODE, THE PLATE CURRENT BECOMES A FUNCTION OF BOTH PLATE VOLTAGE AND GRID VOLTAGE;

$$\text{i. e.,} \quad I_P = F(E_G, E_P) \qquad (3)$$

THE ABOVE RELATION MEANS THAT THE SPACE CURRENT IS SOME FUNCTION OF THE GRID AND PLATE VOLTAGES. REFERRING TO

Child's law mentioned above, $I = K V^{\frac{3}{2}}$, (2) V here is a quantity proportional to the normal electrostatic field at the cathode surface produced by the combination of the individual fields of the grid and plate respectively, and by introducing a factor that will express the relative importance of grid voltage over plate voltage resulting from the fact that the grid is nearer the cathode than the plate, we get the following relation:

$$I_P = K\,(\mu E_G + E_P)^{\frac{3}{2}} \qquad (4)$$

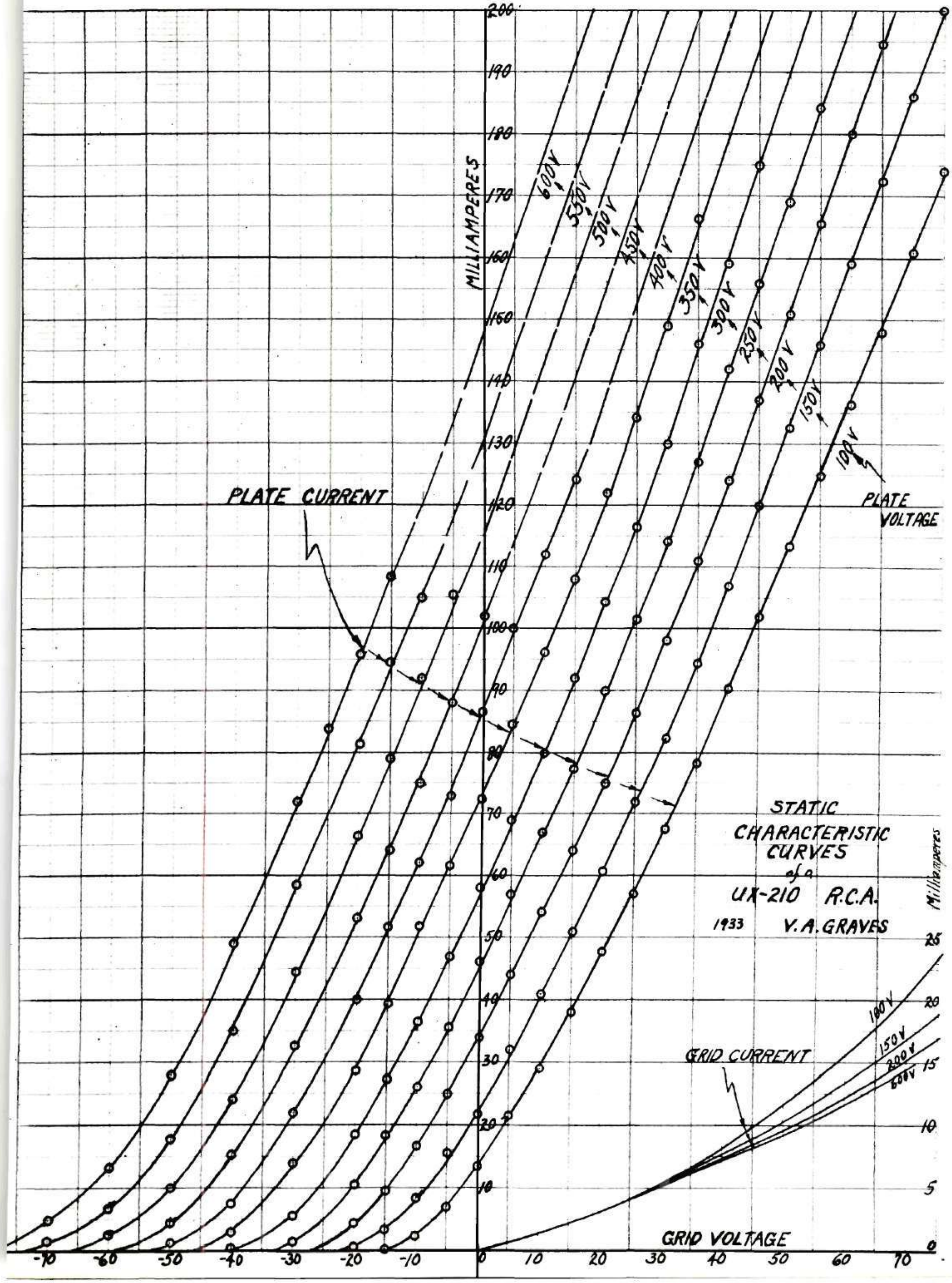
The factor μ (mu) is introduced as an amplification factor and means that a change in grid voltage is μ times as effective in changing the plate current as the same change in plate voltage. The same equation is given by various authors in modified forms:

$$I_P = K'\left(E_G + \frac{E_P}{\mu}\right)^{\frac{3}{2}}$$

$$I_P = F\,(\mu E_G + E_P)$$

In the above equations we have a relation in which the plate current is dependent on the grid and plate voltages. Curves plotted between these three variables are called "characteristic curves" and in Figure 3 one such set of curves for a UX-210 tube will be found. This tube was chosen for the test because it is a fair representation of the entire field of triodes. The UX-210 is a relatively low-power transmitting tube. It has a power output rating of about 10 or 15 watts. This power is determined entirely by the amount of energy that can be dissipated at the plate without overheating. In order to derive the most power from the tube and keep within safe

Fig. 3


MILLIAMPERES
600V
550V
500V
450V
400V
350V
300V
250V
200V
150V
100V
PLATE VOLTAGE
PLATE CURRENT
STATIC CHARACTERISTIC CURVES of a UX-210 R.C.A.
1933 V. A. GRAVES
Milliamperes
GRID CURRENT
GRID VOLTAGE

LIMITS THE EFFICIENCY MUST BE AS HIGH AS POSSIBLE. THUS IF THE SAFE PLATE DISSIPATION IS CONSIDERED 10 WATTS THEN 5 WATTS MAY BE TAKEN FROM THE OUTPUT WITH AN EFFICIENCY OF 30% WHILE IF 10 WATTS ARE TAKEN FROM THE OUTPUT THEN THE EFFICIENCY MUST BE RAISED TO 50%. THUS IN VACUUM TUBES AS IN OTHER ELECTRICAL DEVICES A HIGH EFFICIENCY IS DESIRABLE, AND STEPS ARE TAKEN TO PRODUCE EFFICIENCIES AS GREAT AS POSSIBLE CONSISTENT WITH THE RATING OF THE TUBE. THE 210 TUBE HAS A THORIATED-TUNGSTEN FILAMENT USING 7.5 VOLTS AT 1.25 AMPERES. THE TUBE REQUIRES VARIOUS PLATE VOLTAGES DEPENDING UPON THE GRID BIAS USED. THE VOLTAGE AMPLIFICATION FACTOR IS APPROXIMATELY 8.

IN THE EQUATION, $I_P = K\,(\mu E_G + E_P)^{\frac{3}{2}}$, (4)

IF E_G IS EQUAL TO ZERO, THEN THERE REMAINS BUT A SIMPLE EXPONENTIAL EQUATION BETWEEN PLATE VOLTAGE AND PLATE CURRENT, WHICH, IF PLOTTED ON LOGARITHMIC PAPER, WILL GIVE A STRAIGHT LINE. THE Y INTERCEPT WILL BE THE VALUE OF THE LOGARITHM OF THE CONSTANT AND THE SLOPE OF THE LINE WILL BE THE VALUE OF THE EXPONENT. THE EXPERIMENTAL RESULTS WERE PLOTTED AS SHOWN IN FIGURE 5 IN ORDER TO ASCERTAIN HOW NEARLY THIS TUBE APPROACHED THE IDEAL CASE OF ELECTRON EMISSION. WHEN THE EXPONENTIAL EQUATION IS REDUCED TO LOGARITHMIC FORM, THE EQUATION $I_P = K\,E_P^{\frac{3}{2}}$ BECOMES:

$$\log I_P = \log K + M \log E_P \qquad (5)$$

WHERE M REPRESENTS THE SLOPE OF THE EXPERIMENTAL CURVE AND MAY OR MAY NOT BE $\frac{3}{2}$ ACCORDING TO WHETHER OR NOT THE TUBE OBEYS STRICTLY THE THEORETICAL LAWS. TO ELIMINATE THE PER-

SONAL ERROR IN FITTING THE STRAIGHT LINE TO THE DATA, RESORT WAS MADE TO THE METHOD OF LEAST SQUARES. THIS METHOD MAKES IT POSSIBLE TO OBTAIN THE MOST ACCURATE REPRESENTATION OF DATA IN MATHEMATICAL EXPRESSIONS. THE FOLLOWING EXPRESSIONS WERE DETERMINED IN ORDER TO MAKE USE OF MACHINE CALCULATION:

$$(\text{SLOPE})\ M = \frac{N\sum XY - \sum X \sum Y}{N\sum X^2 - (\sum X)^2} \qquad (7)$$

$$(\text{INTERCEPT})B = \frac{\sum Y \sum X^2 - \sum X \sum XY}{N\sum X^2 - (\sum X)^2} \qquad (8)$$

THE ABOVE FORMULAS APPLY ONLY WHEN THE DATA ARE OF SUCH FORM AS TO INDICATE A LINEAR RELATION. N DESIGNATES THE NUMBER OF POINTS USED IN THE DATA. $\sum X$ REPRESENTS THE SUM OF N ITEMS PLOTTED ALONG THE X AXIS. LIKEWISE THE REMAINDER OF THE QUANTITIES IN THE FORMULAS ARE ALSO THE SUMMATION OF THE Y VARIABLES AND PRODUCTS OF THE X AND Y VALUES.

THE VALUES THAT WERE USED ARE AS FOLLOWS:

	I_p M.A.	E_p VOLTS	LOG I_p	LOG E_p
1	13.3	100.	1.12385	2.00000
2	23.0	150.	1.36173	2.17609
3	34.0	200.	1.53148	2.30103
4	46.0	250.	1.66276	2.39794
5	58.0	300.	1.76343	2.47712
6	72.3	350.	1.85914	2.54407
7	86.5	400.	1.93702	2.60097
8	102.0	450.	2.00860	2.65321
	435.1	2200.	13.24801	19.15043

$\Sigma xy = 32.187505$ $\Sigma x^2 = 46.19320689$

$N = 8$

$$M = \frac{3.79495758}{2.80668590} = 1.352$$

$$\log B = \frac{-4.436508}{2.8066859} = -1.580693$$

$\log B = 8.419307 - 10$

$B = .002626$ M. A. OR $.00002626$ AMPERES

IF THE PLATE CURRENT IS HELD CONSTANT WE HAVE A RELATION SIMILAR TO THE FOLLOWING:

$$I_P = K\ (\mu E_G + E_P)^M = C; \quad (9)$$

THEN,

$$\mu E_G + E_P = C'. \quad (10)$$

THIS IS A LINEAR RELATION BETWEEN PLATE VOLTAGE AND GRID VOLTAGE AND IF PLOTTED SHOULD GIVE A STRAIGHT LINE. THIS WAS DONE IN FIGURE 4 AND THE SLOPE OF EACH LINE WAS DETERMINED, WHICH GAVE A VALUE FOR THE AMPLIFICATION FACTOR OR μ OF THE TUBE. THIS FACTOR RANGES BETWEEN 8.2 AND 8.5 WITH AN AVERAGE OF 8.32 OVER THE RANGE INVESTIGATED. SINCE THE FACTOR μ IS PRACTICALLY CONSTANT OVER THE RANGE THAT WE ARE INVESTIGATING THEN THE EQUATION OF PLATE CURRENT MAY BE EXPRESSED AS,

$$I_P = K'\ (\mu E_G + E_P) + B \quad (12)$$

SUBSTITUTING VALUES DETERMINED FOR K' AND B:

$$I_P = .0002536\ (\mu E_G + E_P) - .01536 \quad (13)$$

IN EQUATION(13) THE SLOPE OF THE CURVE REPRESENTS THE CHANGE IN CURRENT WITH A CERTAIN CHANGE IN VOLTAGE; IT IS THEREFORE THE RECIPROCAL OF THE AVERAGE PLATE RESISTANCE OVER THE POR-

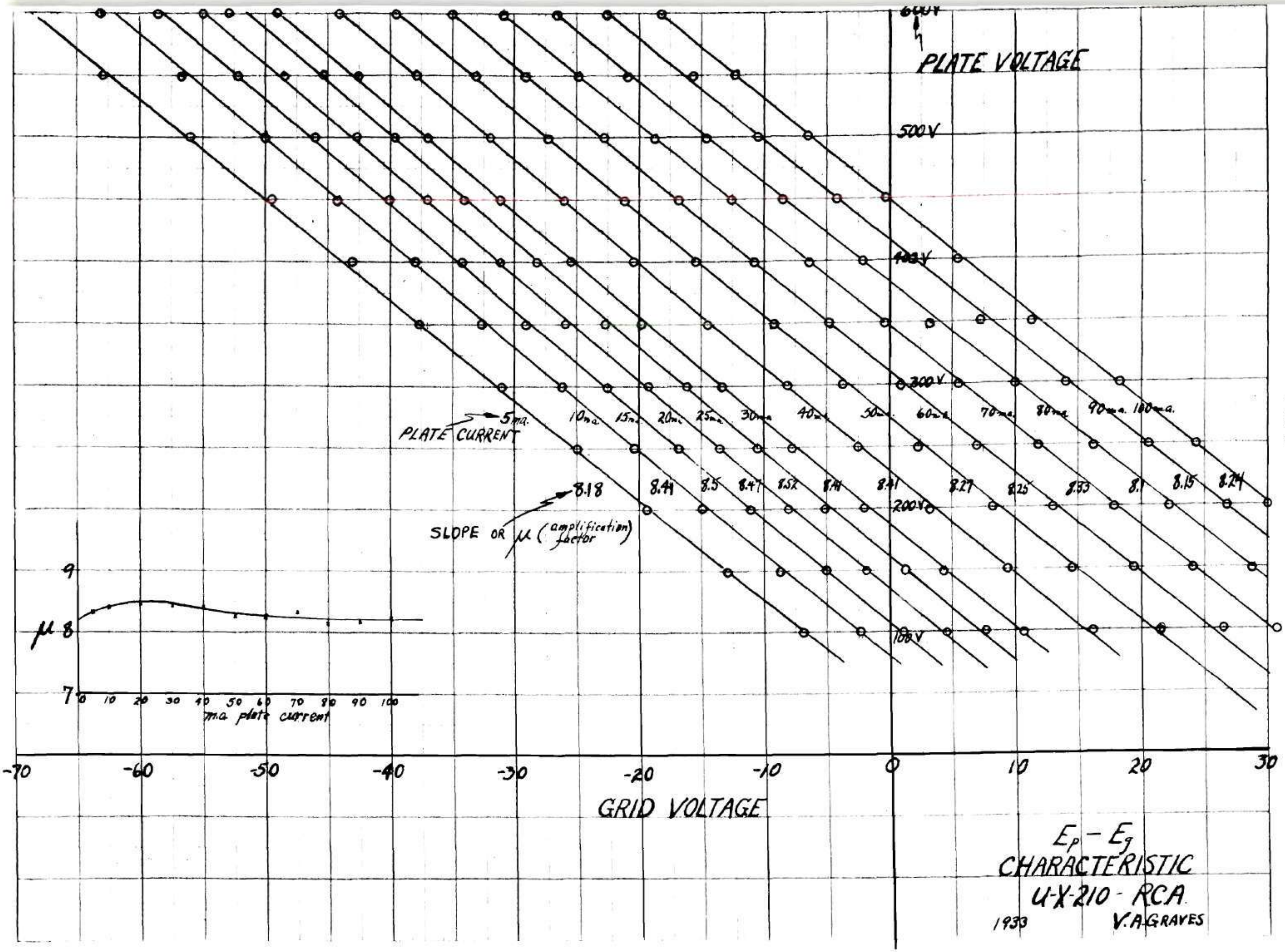


PLATE VOLTAGE
500V
400V
300V
200V
100V
PLATE CURRENT
5ma.
10ma.
15ma.
20ma.
25ma.
30ma.
40ma.
50ma.
60ma.
70ma.
80ma.
90ma.
100ma.
SLOPE OR μ (amplification factor)
8.18
8.5
9
μ 8
7
0 10 20 30 40 50 60 70 80 90 100
ma plate current
-70 -60 -50 -40 -30 -20 -10 0 10 20 30
GRID VOLTAGE
$E_p - E_g$
CHARACTERISTIC
U-X-210 - RCA
1933
V.A.GRAVES

FIG. 4

Fig. 5

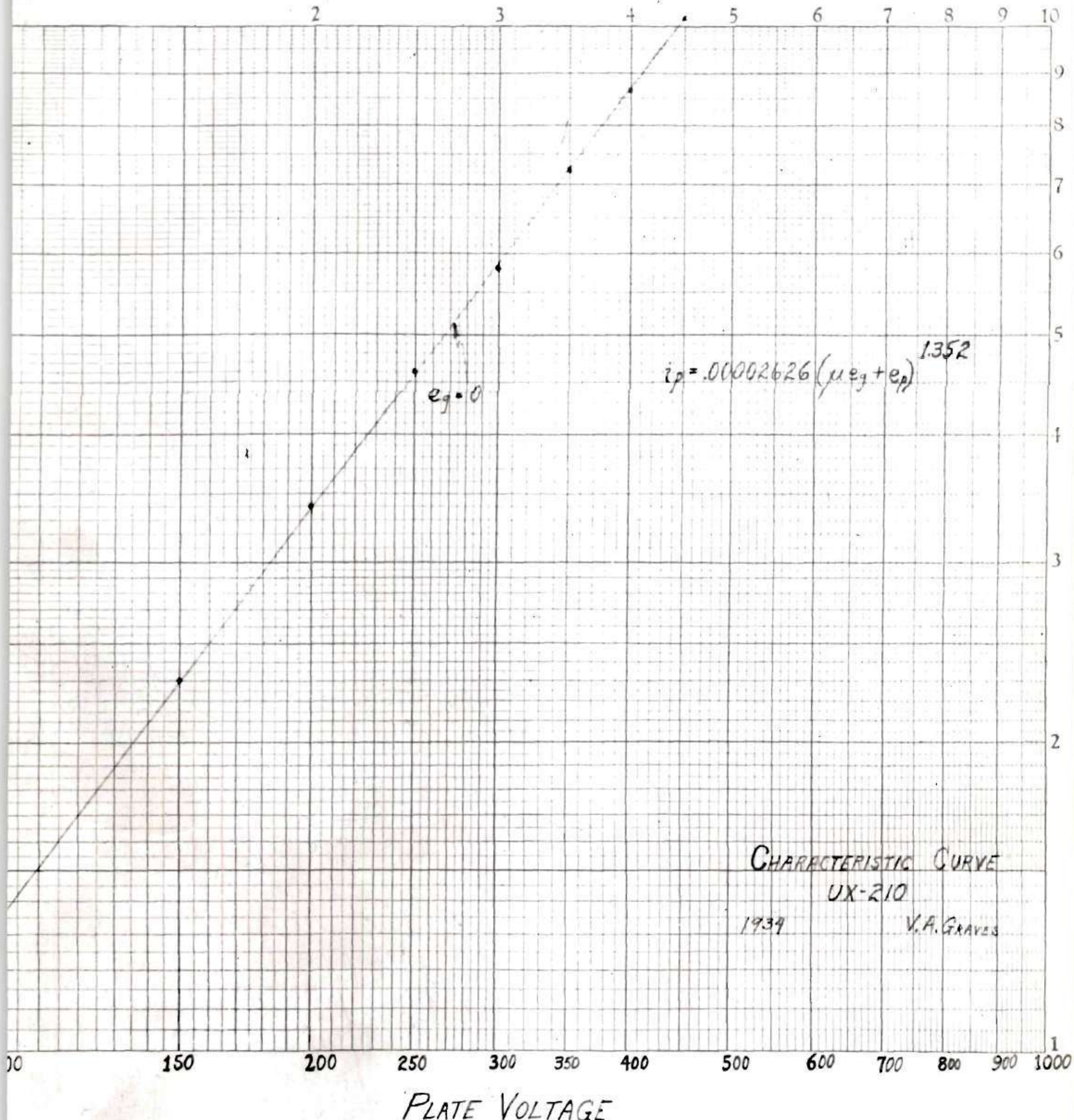


Plate Current
2 3 4 5 6 7 8 9 10
9 8 7 6 5 4 3 2 1
$e_g = 0$
$i_p = .00002626(\mu e_g + e_p)^{1.352}$
CHARACTERISTIC CURVE
UX-210
1934
V. A. GRAVES
150 200 250 300 350 400 500 600 700 800 900 1000
PLATE VOLTAGE

tion of the characteristic to which it is applied. Equations (11) and (13) are similar in type and nature, and they represent the same data. The only difference between them is that in (11) we have an equation which fits the data very well. The exponential form is more difficult to use, however, whereas equation (13) is easy to work with and fits the data very well except at the upper and lower limits. This comparison is shown in Figure 6.

If equation (13) is differentiated partially with respect to E_p, then we shall have an equation

$$\frac{\partial i_p}{\partial E_p} = .0002536 \qquad (14)$$

Equation (14) means that if we may assume a straight line relation between plate voltage and plate current, then the plate current changes .0002536 amperes every time the plate voltage changes one volt. The reciprocal of this number is the average plate resistance; it is 3940 ohms. Another useful constant which is referred to as mutual conductance is the ratio of the amplification factor to plate resistance. By using the above values we obtain,

$$G_M = \frac{8.32}{3940} = 2110. \text{ micromhos.} \qquad (15)$$

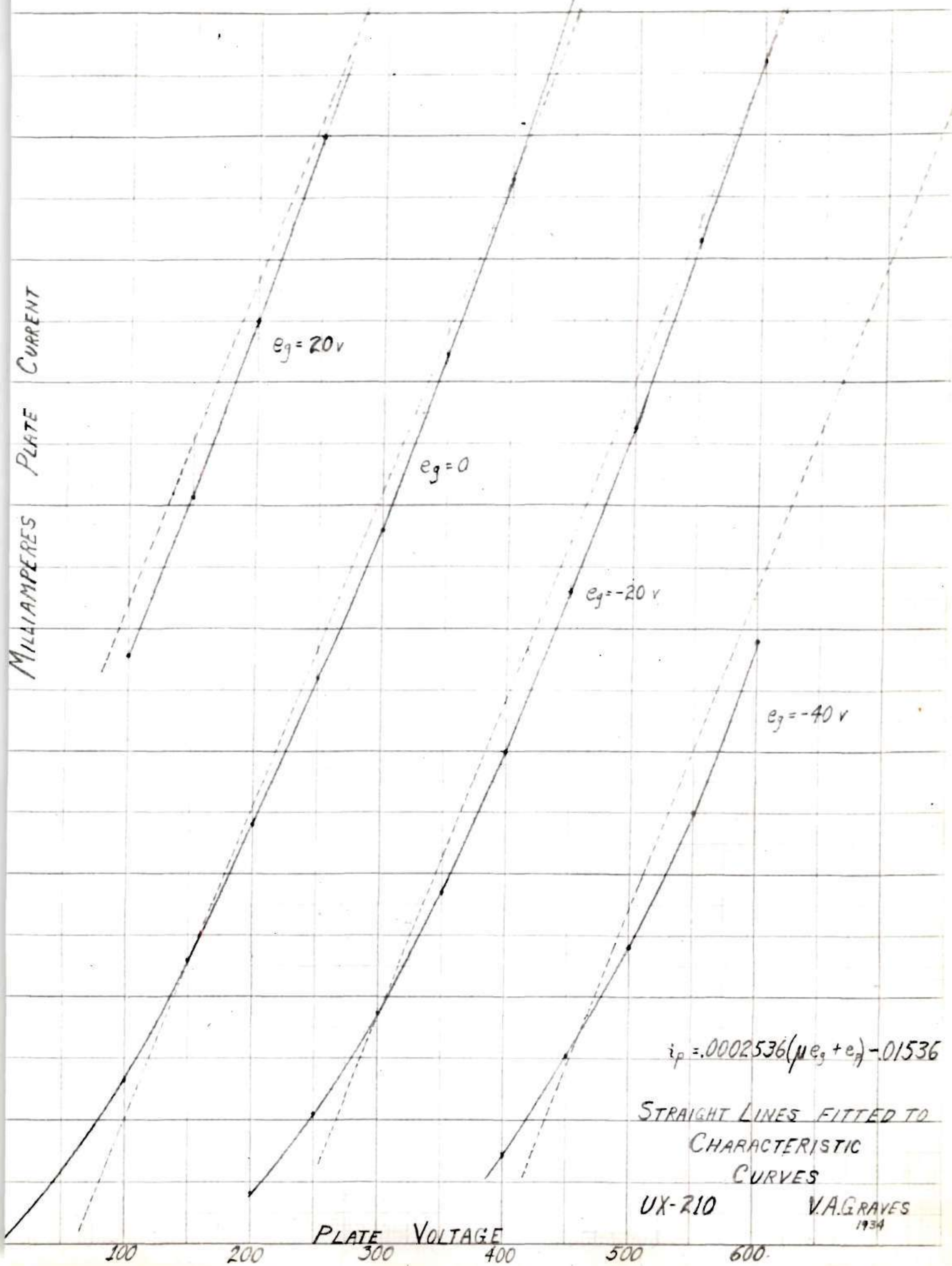
These values of tube constants may be used when dealing with average relationships. For the sake of clarity, they are now repeated:

Amplification factor (av.) = 8.32

Plate resistance (av.) = 3940. ohms.

Mutual conductance (av.) = 2110. micromhos

Fig. 6


Milliamperes Plate Current
$e_g = 20v$
$e_g = 0$
$e_g = -20v$
$e_g = -40v$
$i_p = .0002536(\mu e_g + e_p) - .01536$
Straight Lines Fitted to Characteristic Curves
UX-210
V.A.Graves
1934
Plate Voltage
100
200
300
400
500
600

By using the more exact exponential form in (11) and differentiating partially with respect to E_p, we obtain:

$$\frac{\partial I_p}{\partial E_p} = .0000355(\mu E_G + E_p)^{.352} \qquad (16)$$

Equation (16) shows how the plate resistance varies as the grid and plate voltages change. When $E_G = 0$ and $E_p = 350$ volts

$$R_p = \frac{1}{.0000355\ (350)^{.352}} = 5330.\ \text{ohms}$$

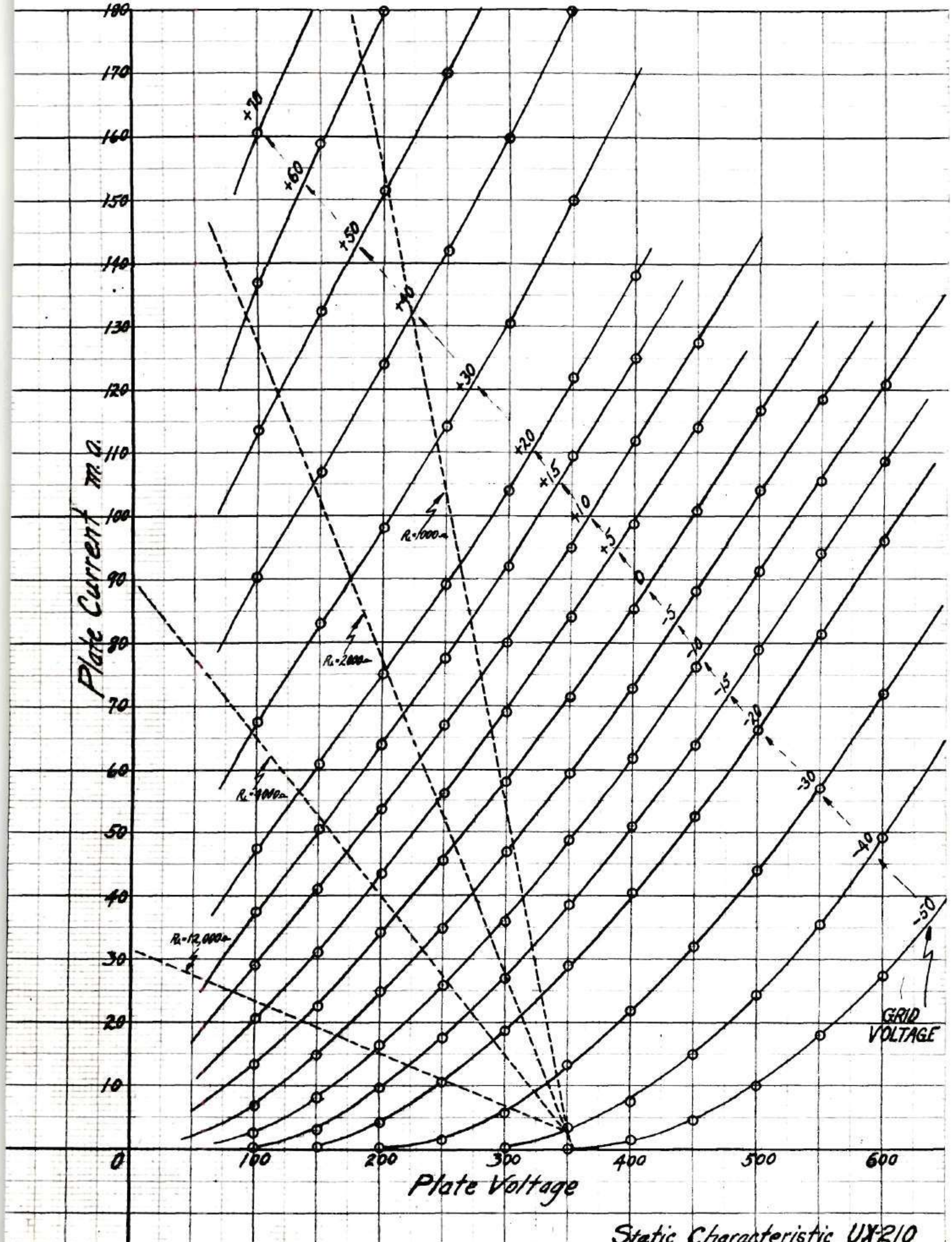
$$G = \frac{8.32}{5330.} = 1560.\ \text{micromhos.}$$

The characteristic curves were also expressed in the form of infinite series with all but the first three terms omitted. Thus:

$$I_p = .00009921\ (\mu E_G + E_p) + .0000038\ (\mu E_G + E_p)^2 - .000000000221\ (\mu E_G + E_p)^3 \qquad (17)$$

The fourth and succeeding terms were very much smaller than the third so they were neglected.

Fig. 7



Static Characteristic UX210

V. A. Graves.

THEORETICAL APPLICATION

THE PRECEDING STATIC CHARACTERISTICS HAVE BEEN EXPRESSED WITH MATHEMATICAL PRECISION BY PASSING A CURVE THROUGH A SERIES OF POINTS WHICH HAVE BEEN DETERMINED EXPERIMENTALLY. THIS PROVES SATISFACTORY WITHIN THE LIMITS OF THE EQUATIONS, YET THERE ARE INSTANCES WHEN THIS IS NOT ADEQUATE. ANY RELATION THAT IS CONTINUOUS MAY BE EXPRESSED BY THE TOTAL DIFFERENTIAL EQUATION,

$$D\,I_p = \frac{\partial I_P}{\partial E_P}\,D\,E_P + \frac{\partial I_P}{\partial E_G}\,D\,E_G \qquad (18)$$

IF BY THE NATURE OF THE PROBLEM OR TO SIMPLIFY THE TREATMENT, THE PARTIAL DERIVATIVES ARE ASSUMED CONSTANT, THEN THE RELATION BECOMES LIKE THE ONE WE HAVE OBSERVED. SHOULD THE LINEAR RELATION PROVE SATISFACTORY, THEN THE EQUIVALENT CIRCUIT WILL BE AS FOLLOWS;

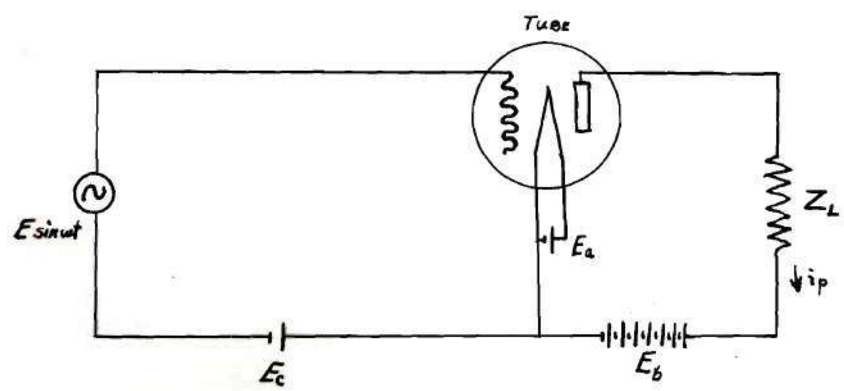


FIG 8

NOTING THE DIAGRAM, WE MAY OBSERVE THAT THE INSTANTANEOUS GRID VOLTAGE (E_G) AND PLATE VOLTAGE WILL BE

$$E_p = E_C + E \sin \omega T, \quad \text{AND}$$

$$E_P = E_B - I_P Z_L$$

ACCORDING TO PREVIOUS DETERMINATION,

$$I_P = .0002536\,(\mu E_G + E_P) - .01536 \qquad (13)$$

OR

$$I_P = \frac{\mu E_G + E_P}{3940} - .01536 \quad (\text{AMPERES})$$

SUBSTITUTING INSTANTANEOUS VALUES FOR E_G AND E_P, WE OBTAIN:

$$I_P = \frac{\mu(E_C + E \sin \omega T) + E_B - I_P Z_L}{3940} - .01536$$

SIMPLIFYING THE EQUATION YIELDS THE FOLLOWING RESULT:

$$I_P(3940 + Z_L) = \mu E_C + \mu E \sin \omega T + E_B - 60.5 \qquad (18)$$

SINCE THE PLATE CURRENT WILL BE THE COMBINATION OF A DIRECT CURRENT WHICH DETERMINES THE OPERATING POINT, AND AN ALTERNATING CURRENT, WE MAY WRITE:

$$(\text{D.C.}) \quad I_P = \frac{\mu E_C + E_B - 60.5}{3940 + R_L} \qquad (19)$$

$$(\text{A.C.}) \quad I_P = \frac{\mu E \sin \omega T}{3940 + R_L} \qquad (20)$$

EQUATION (20) MAY BE UTILIZED AS A BASIS FOR THE EQUIVALENT CIRCUIT OF A TRIODE, AS SHOWN.

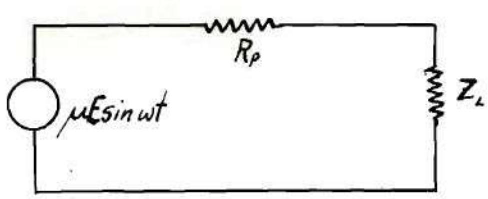


Fig 8a

THIS EQUATION AND EQUIVALENT CIRCUIT ARE USEFUL ONLY SO LONG AS THE CHARACTERISTIC CURVES SIMULATE STRAIGHT LINES OVER THE OPERATING RANGE.

It is an accepted fact that any periodic wave may be represented by the sum of a series of sine and cosine waves with any degree of accuracy desired. Such a wave of current in the plate circuit of a vacuum tube when the voltage applied to the grid is of a periodic nature will be

$$i = A_1 \sin\theta + A_2 \sin 2\theta + A_3 \sin 3\theta + \text{---------}$$

$$+ B_0 + B_1 \cos\theta + B_2 \cos 2\theta + B_3 \cos 3\theta + \text{-----} \tag{21}$$

The coefficients are determined as shown:

$$A_N = \frac{1}{\pi}\int_0^{2\pi} (\sin N\theta)\, i \, d\theta \tag{22}$$

$$B_N = \frac{1}{\pi}\int_0^{2\pi} (\cos N\theta)\, i \, d\theta \tag{23}$$

$$B_0 = \frac{1}{2\pi}\int_0^{2\pi} i \, d\theta \tag{24}$$

By proper selection of axes, either the A coefficients or the B coefficients may often be reduced to zero, so that the computation may be simplified. The constant or direct current term will be zero if there is as much area below the axis as there is above; otherwise it will be either positive or negative according to whether there is more area above or below the axis respectively. When the por-

TION OF THE COMPLEX WAVE LYING BETWEEN π AND 2π RADIANS IS A MIRROR IMAGE OF THE PORTION LYING BETWEEN 0 AND π RADIANS, THE SERIES CONTAINS NO SINE TERMS. AN EXAMPLE IS A FULLY RECTIFIED SINE WAVE. THIS MAY ALSO BE WRITTEN:

$$F(\pi + \omega t) = F(\pi - \omega t)$$

WHEN $F(\pi + \omega t) = -F(\pi - \omega t)$, THE SERIES CONTAINS NO COSINE TERMS. AN EXAMPLE IS THE WAVE OF TRANSFORMER MAGNETIZING CURRENT.

THE POWER THAT CAN BE CONTROLLED BY A VACUUM TUBE DEPENDS ON THE RATE AT WHICH THE LOSSES MAY BE DISSIPATED. THUS, AS WITH MOST ELECTRICAL DEVICES, IT IS DESIRABLE TO OBTAIN AS HIGH EFFICIENCY AS POSSIBLE SO THAT THE LOSSES FOR ANY PARTICULAR VALUE OF INPUT WILL BE SMALL. THE EFFICIENCY IS MERELY THE RATIO OF POWER CONVERSION, OR IT IS THE PRODUCT OF VOLTAGE DEVELOPED ACROSS THE TANK CIRCUIT AND THE CURRENT FLOWING IN IT DIVIDED BY THE DIRECT POWER THAT IS SUPPLIED TO THE TUBE.

$$\text{EFF.}_{(\text{PLATE})} = \frac{E_{Z_L} \; I_{P_1}}{2 \; E_B \; I_{P_0}} \qquad (25),$$

WHERE Z_L IS ASSUMED TO BE A PURE RESISTANCE AT THE FREQUENCY OF OPERATION. A PROBLEM WILL BE SOLVED TO DETERMINE THE EFFICIENCY OF THE 210-TYPE TUBE OPERATING AS A CLASS B AMPLIFIER, AND THIS WILL LATER BE CHECKED BY EXPERIMENT. THE AMPLIFICATION FACTOR WILL BE TAKEN AS THE AVERAGE DETERMINED IN FIG. 4, OR 8.32. THE PLATE VOLTAGE USED IN THE EXPERIMENT WAS 350 VOLTS, SO THIS VALUE WILL BE ASSUMED IN THE PROBLEM. IF THE MINIMUM PLATE VOLTAGE IS

TAKEN AS 100 VOLTS AND THE MAXIMUM GRID VOLTAGE AS 70 VOLTS AND THE GRID BIAS AS 43.5 VOLTS, AND THE PLATE CURRENT INVESTIGATED OVER A COMPLETE CYCLE WE MAY BE ABLE TO DETERMINE THE TANK AND PLATE CURRENTS AND THUS OBTAIN THE EFFICIENCY. THE FOLLOWING DIAGRAM SHOWS THE INSTANTANEOUS VOLTAGES AND CURRENSS ASD FUNCTIONS OF TIME. THE FOLLOWING TABLE ILLUSTRATES THE METHOD FOR CALCULATING THE DIRECT CURRENT AND FUNDAMENTAL FREQUENCY COMPONENTS OF THE PLATE CURRENT AND GRID CURRENT.

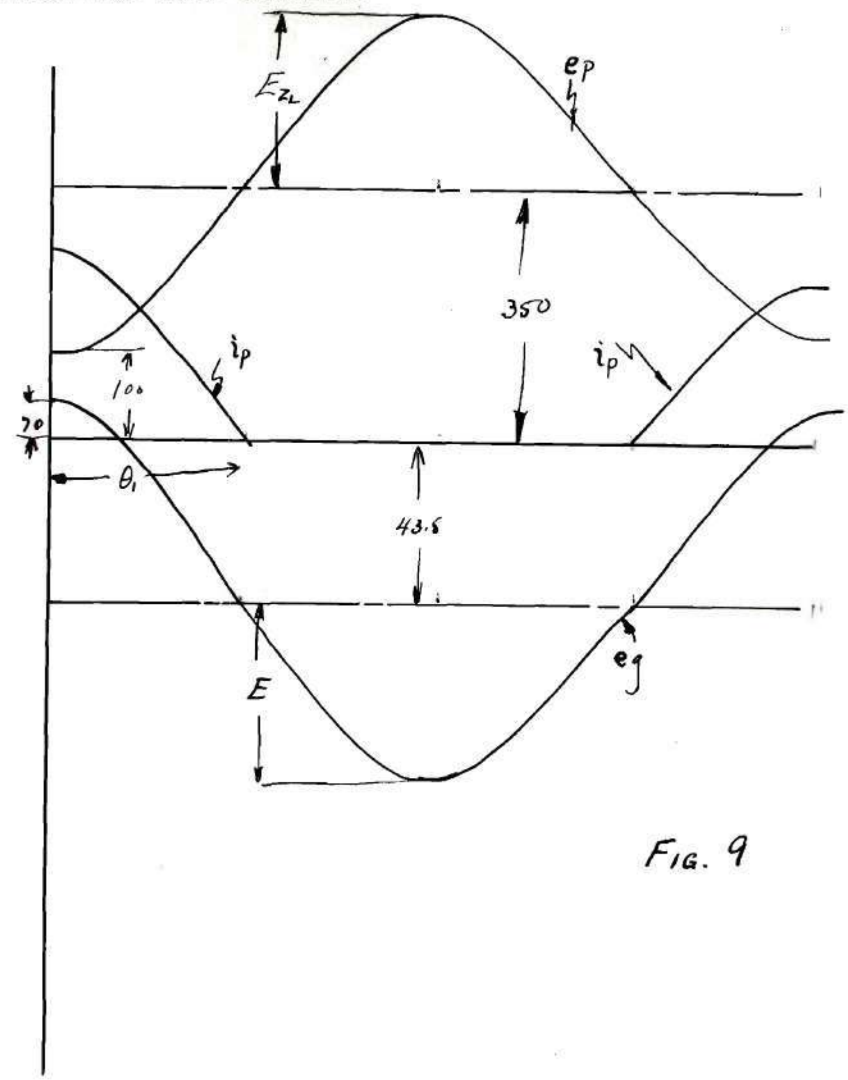


FIG. 9

Table on page 30

-POINT BY POINT METHOD-

TABLE OF INSTANTANEOUS VALUES OF PLATE AND GRID VOLTAGE AND CURRENT

θ^o	Cos θ	$E Z_L$ Cos θ	E_P	E Cos θ	E_G	I_P	I_G	I_P Cos θ	I_G Cos θ
0	1.0000	250.0	100.0	113.5	70.	161.0	20.5	161.0	20.5
10	.9847	246.0	104.0	111.5	68.	159.0	19.	156.5	18.7
20	.9397	234.5	115.5	106.4	62.9	147.0	16.	138.0	15.0
30	.8660	216.5	133.5	98.4	54.9	136.0	12.5	117.9	10.8
40	.7660	191.5	158.5	87.0	43.5	120.0	8.5	92.0	6.5
50	.6430	160.8	189.2	73.0	29.5	94.0	5.0	60.5	3.2
60	.5000	125.0	225.0	56.8	13.2	67.0	2.0	33.5	1.0
70	.3420	85.5	264.5	38.8	-4.7	39.0	0.	13.4	0
80	.1736	43.5	306.5	19.7	-23.8	14.0	0.	2.4	0
90	.0000	9.0	350.0	0.0	-43.5	1.0	0.	0	0.
100	-.1738	-43.4	393.4	-19.7	-63.2	0	0	0	0
110	-.3420	-85.5	435.5	-38.8	-82.3	θ	0	0	0
120	-.5000	-125.0	475.0	-56.8	-100.8	0	0	0	0
130	-.6430	-160.8	510.8	-73.0	-	0	0	0	0
140	-.7660	-191.5	541.5	-87.0	-	0	0	0	
150	-.8660	-216.5	566.5	-98.4	-	0	0		
160	-.9400	-234.5	584.5	-106.4	-	0	0		
170	-.9850	-246.0	596.0	-111.5	-	0	0		
180	-1.0000	-250.0	600.0	-113.5	-	0	0		

It has been shown already that

$$B = \frac{1}{2\pi} \int_0^{2\pi} i \, d\theta \qquad (24)$$

Application of the point by point method of integration yields the following:

$$I_{P_0} = \frac{1}{2\pi} \times \frac{2\pi}{18} \left(\frac{Y_0 + Y_N}{2} + Y_1 + Y_2 + Y_3 + Y_4 + \cdots Y_{N-1} \right)$$

or

$$I_{P_0} = \frac{1}{18} \left(\frac{Y_0}{2} + Y_1 + Y_2 + Y_3 + Y_4 + \cdots\cdots + Y_{N-1} \right)$$

(Y_N is neglected since it is zero.)

The value of the interval, ΔX, is 10° or $\frac{\pi}{18}$ radians. The value of the summation is doubled because integration is carried out over half a cycle only.

Hence, $I_{P_0} = \frac{857.5}{18} = 47.6$ ma.

Also, $$I_{P_1} = B_1 = \frac{1}{\pi} \int_0^{2\pi} i_P \cos \theta \, d\theta = \frac{2}{\pi} \int_0^{\pi} i_P \cos \theta \, d\theta \quad (23)$$

The above equation (23) is for the fundamental component of plate current. When the tank circuit is tuned to resonance at the fundamental frequency, the impedance offered to higher harmonics is so small and of such a low power factor that the tank circuit absorbs a negligible amount of power at harmonic frequencies.

$$I_{P_1} = \frac{\pi}{18} \times \frac{2}{\pi} \left(\frac{Y'_0}{2} + Y'_1 + Y'_2 + \cdots\cdots Y_{N-1} \right),$$

WHERE $Y' = Y \cos\theta$. USING TABULATED VALUES YIELDS:

$$I_{P_1} = \frac{694.7}{9} = 77.1 \text{ MA.}$$

THE EFFICIENCY IS:

$$\text{EFF.} = \frac{77.1 \times 250}{2 \times 350 \times 47.6} = 57.8\%$$

THE CURRENTS ARE EXPRESSED IN MILLIAMPERES, SINCE UNITS ARE IMMATERIAL IN A RATIO OF THIS SORT. THE REASON FOR THE FACTOR 2 IN THE DENOMINATOR IS THAT BOTH A.C. VOLTAGE AND CURRENT ARE EXPRESSED AS MAXIMUM VALUES RATHER THAN EFFECTIVE VALUES.

BY USING EQUATIONS (13) AND (24) WE MAY DERIVE A THEORETICAL VALUE FOR I_{P_1} AND I_{P_0}

IN FIG. 9 IT WILL BE SEEN THAT

$e_G = -E_C + E\cos\theta$, AND

$e_P = E_B - E_{Z_L}\cos\theta$.

THEN
$$i_p = \frac{\mu(-E_C + E\cos\theta) + E_B - E_{Z_L}\cos\theta}{3940} - .01536. \quad (26)$$

$$I_{P_1} = \frac{2}{\pi}\int_0^{\theta_1} i_p \cos\theta \, d\theta, \quad (23)$$

WHERE θ_1 IS THE ANGLE OF CUTOFF AND FOR THE PROBLEM JUST REFERRED TO IT IS EQUAL TO 90°. SINCE THE CUTOFF ANGLE IS 90°, WE HAVE THE FOLLOWING RELATION WHICH SIMPLIFIES THE ABOVE EQUATION OF PLATE CURRENT: $E_B = -\mu E_C$. THIS NOW BECOMES A

TYPICAL PROBLEM FOR A CLASS B AMPLIFIER. SUBSTITUTING EQ. (26) IN EQ. (23) AND SIMPLIFYING, WE GET EQ. (27):

$$I_{P_1} = \frac{\mu E - \frac{242}{\pi}}{Z_L + 7880} \qquad (27)$$

WHERE E_{Z_L} IS REPLACED BY $Z_L I_{P_1}$

SINCE $E_{Z_L} = Z_L I_{P1}$,

$$I_{PO} = \frac{1}{\pi}\int_0^{\pi/2} i \, d\theta = \frac{1}{\pi}\left\{\left(\frac{\mu E - E_{Z_L}}{3940}\right) - .00768\pi\right\}$$

$$I_{PO} = \frac{2}{\pi} I_{P_1} - .00145 \qquad (28)$$

THE LOAD IMPEDANCE WHICH IN THIS CASE IS A PURE RESISTANCE IS EQUAL TO 3240 OHMS (E_{Z_L}/I_{P_1}) AND WHEN E_G EQUALS 70 VOLTS MAX. AND μ EQUALS TO 8.32,

$$I_{P_1} = \frac{\mu\, 113.5 - \frac{242}{\pi}}{3240 + 7880} = \frac{945 - 77}{11,120} = 78. \text{ MA.}$$

THE RESULT, 78 MA., CHECKS WELL WITH THE RESULT OF THE POINT-BY-POINT METHOD, WHICH GAVE 77.1 MA. AND DEMONSTRATES THAT THE EQUATION CAN BE USED TO PREDICT TUBE OPERATION AND DETERMINE EFFICIENCIES. WHEN EQUATION (28) IS SOLVED, WE GET 48.2 MA. WHICH COMPARES FAVORABLY WITH 47.6 MA. FOR THE POINT-BY POINT METHOD. THE EFFICIENCY IS OBVIOUSLY ABOUT THE SAME.

EQUATION (27) MAY BE WRITTEN:

$$I_{P_1} = \frac{E - 77.}{Z_L + 2R_P} \qquad (29)$$

For the example used before, where E equals 113.5 volts, equation (29) may be written:

$$Z_L + 2\,R_P = \frac{868}{I_{P_1}}$$

or

$$I_{P_1} = \frac{868}{Z_L + 2\,R_P}$$

If we are at liberty to select various loads, we may select pure resistance loads and also may assign any value to them. Thus resistance loads of 1000, 2000, 4000, 7000, 12000, ohms have been assumed. From the equation above, I_{P_1} has been calculated and is listed below:

R_L	1000	2000	4000	7000	12000
I_{P_1} (max)	97.7 ma.	87.8 ma.	73. ma.	58.3 ma.	43.6 ma.
I_{P_1} (eff.)	69. ma.	62. ma.	51.6 ma.	41.2 ma.	30.8 ma.

-5-

EXPERIMENTAL RESULTS

TESTS WERE MADE BY USING THE 210-TYPE TUBE AS A RADIC FREQUENCY AMPLIFIER AS SHOWN IN THE FIGURE BELOW.

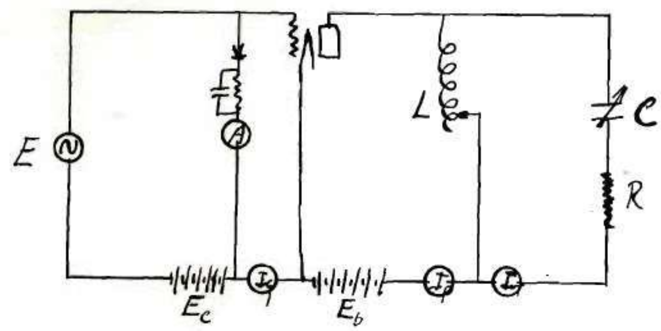
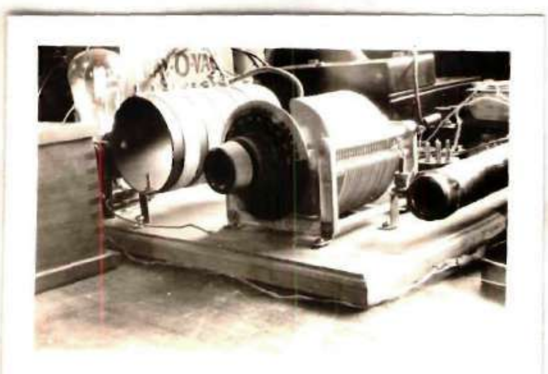
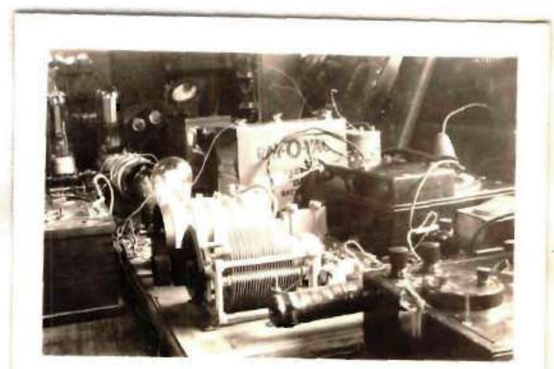


Fig 10

THE PICTURES SHOW THE ARRANGEMENT OF EQUIPMENT AND SET-UP.





THE TANK COIL, L, WAS WOUND IN FIVE SECTIONS SO THAT IT WAS POSSIBLE TO GET FIVE DIFFERENT LOADS WITHOUT THE COMMONLY OBJECTIONABLE "DEAD-END TURNS". THE COIL WAS WOUND ON A FORM 3.5 INCHES IN DIAMETER WITH NO. 24 DOUBLE COTTON COVERED WIRE WITH NO SPACING BETWEEN TURNS.

THE DATA ON THE COILS WERE AS FOLLOWS:

COIL #	TURNS	INDUCTANCE MICROHENRIES	IMPEDANCE 600 K.C.	R EFF. 600 K.C.
1	26	63.0	237.8 OHMS	1.3 OHMS.
2	35	86.25	325.5	1.9
3	49	129.5	488.0	3.1
4	65	176.0	664.0	5.2
5	83	233.5	880.0	7.7

THE DISSIPATIVE RESISTANCE IN THE TANK CIRCUIT HAD A RESISTANCE OF 56. OHMS AT 600. K. C. THE LOAD IMPEDANCE WHEN THE TANK CIRCUIT WAS TUNED TO RESONANCE WAS AS FOLLOWS:

LOAD #	$\dot{Z}_L$	Z_L
1	1000 + J 228	1025 OHMS
2	1840 + J 305	1860
3	4000 + J 457 ,	4025
4	7200 + J 550	7220
5	12200 + J 671	12210

THE CURRENT IN THE TANK CIRCUIT WAS MEASURED BY MEANS OF A 100 MA. THERMOCOUPLE IN CONJUNCTION WITH CAPACITIVE SHUNTS SO AS TO LIMIT THE CURRENT TO THE THERMOCOUPLE RATING. THE THERMOCOUPLE WAS CALIBRATED BY USING

DIRECT CURRENT AND REVERSING THE FLOW SO AS TO COMPENSATE FOR ANY ERROR DUE TO DIRECT CONNECTION OF THE THERMAL JUNCTION TO THE HEATER. ALL METERS USED WERE CALIBRATED AND CHECKED AGAINST A WESTON STANDARD CELL. THE INDUCTANCES AND CAPACITIES WERE MEASURED BOTH BY BRIDGE AND BY RESONANCE METHOD. THE A.C. RESISTANCE OF THE COIL WAS MEASURED BY THE RESISTANCE-VARIATION METHOD AT 600 K. C. THE VARIABLE TANK CONDENSER USED WAS A GOOD GRADE 43 PLATE CONDENSER. THE GRID ALTERNATING VOLTAGE WAS SUPPLIED BY MEANS OF A LABORATORY 50 WATT SELF-EXCITED OSCILLATOR. THIS GRID VOLTAGE WAS MEASURED BY MEANS OF A CALIBRATED RECTIFIER-TYPE VOLTMETER WHICH GAVE THE EFFECTIVE VALUE OF THE APPLIED GRID VOLTAGE.

VARIOUS RUNS WERE MADE AT DIFFERENT TIMES IN ORDER TO CHECK THE ACCURACY OF THE TEST. IN ONE TEST AN AUXILLARY AMPLIFIER USING TWO 50 WATT TUBES AS A SINGLE STAGE, NEUTRALIZED AND IN PUSH-PULL ARRANGEMENT, WAS SET UP IN ORDER TO PROVIDE A LOW IMPEDANCE GENERATOR CAPABLE OF SUPPLYING APPRECIABLE GRID CURRENT WITHOUT WAVE SHAPE DISTORTION. THIS AMPLIFIER MAY BE SEEN IN THE BACKGROUND OF THE ATTACHED PHOTOGRAPHS. AT OTHER TIMES THE DRIVING VOLTAGE WAS TAKEN DIRECTLY FROM TAPS ON THE TANK COIL OF THE SELF-EXCITED OSCILLATOR. THE GRID BIAS WAS SUPPLIED ENTIRELY BY MEANS OF A BATTERY AS SHOWN IN FIG. 10. THE PLATE VOLTAGE WAS SUPPLIED FROM A HIGH VOLTAGE MOTOR-GENERATOR SET. THE FILAMENT WAS HEATED WITH 7.5 V.A.C. VOLTAGE. THE PLATE AND GRID VOLTAGES

WERE TAKEN RELATIVE TO A CENTER-TAPPED RESISTOR CONNECTED ACROSS FILAMENT TERMINALS. THE FREQUENCY WAS MEASURED BY MEANS OF A LABORATORY DYNATRON FREQUENCY-METER. AT ALL TIMES THE FREQUENCY WAS KEPT AT 600 K.C. AND RESONANCE IN THE TANK CIRCUIT WAS INDICATED BY THE DIRECT CURRENT PLATE CURRENT REACHING A MINIMUM VALUE.

THE RELATION BETWEEN RADIO FREQUENCY TANK CURRENT AND R.F. GRID VOLTAGE (EFFECTIVE VALUES) HAS BEEN PLOTTED IN FIG. 11 FOR THE DIFFERENT LOADS. IT SHOULD BE NOTED THAT ALL THE CURVES HAVE LINEAR PORTIONS, IN WHICH RANGE THERE IS A MINIMUM OF DISTORTION, BUT THAT THE CURVES FOR THE HIGHER LOADS HAVE THE SHORTER STRAIGHT PORTIONS. THE BENDING OVER OF THE CURVES IS DUE TO MAXIMUM GRID VOLTAGE BECOMING GREATER THAN THE MINIMUM PLATE VOLTAGE. THERE IS NO APPRECIABLE CURVATURE IN ANY OF THE CURVES UNTIL THE GRID BEGINS TO DRAW CURRENT. THIS CURRENT FLOWS ONLY WHEN THE PEAK DRIVING VOLTAGE IS GREATER THAN THE GRID BIAS. THE DYNAMIC CHARACTERISTICS GIVE THE RELATION BETWEEN THE GRID VOLTAGE AND DIRECT CURRENT PLATE CURRENT AND ARE SHOWN IN FIG. 12.

THE GRID CURRENT IS PLOTTED AGAINST GRID VOLTAGE IN FIG. 13. IT SHOULD BE NOTED THAT IF A LIMITING VALUE OF GRID CURRENT IS STIPULATED THEN THE GRID DRIVING VOLTAGE MUST ALSO BE LIMITED IN ORDER THAT THE GRID CURRENT MAY REMAIN WITHIN ITS PROPER LIMIT FOR THE HIGHER LOADS. FOR INSTANCE, IF 10 MILLIAMPERES IS CHOSEN AS AN

Fig 11

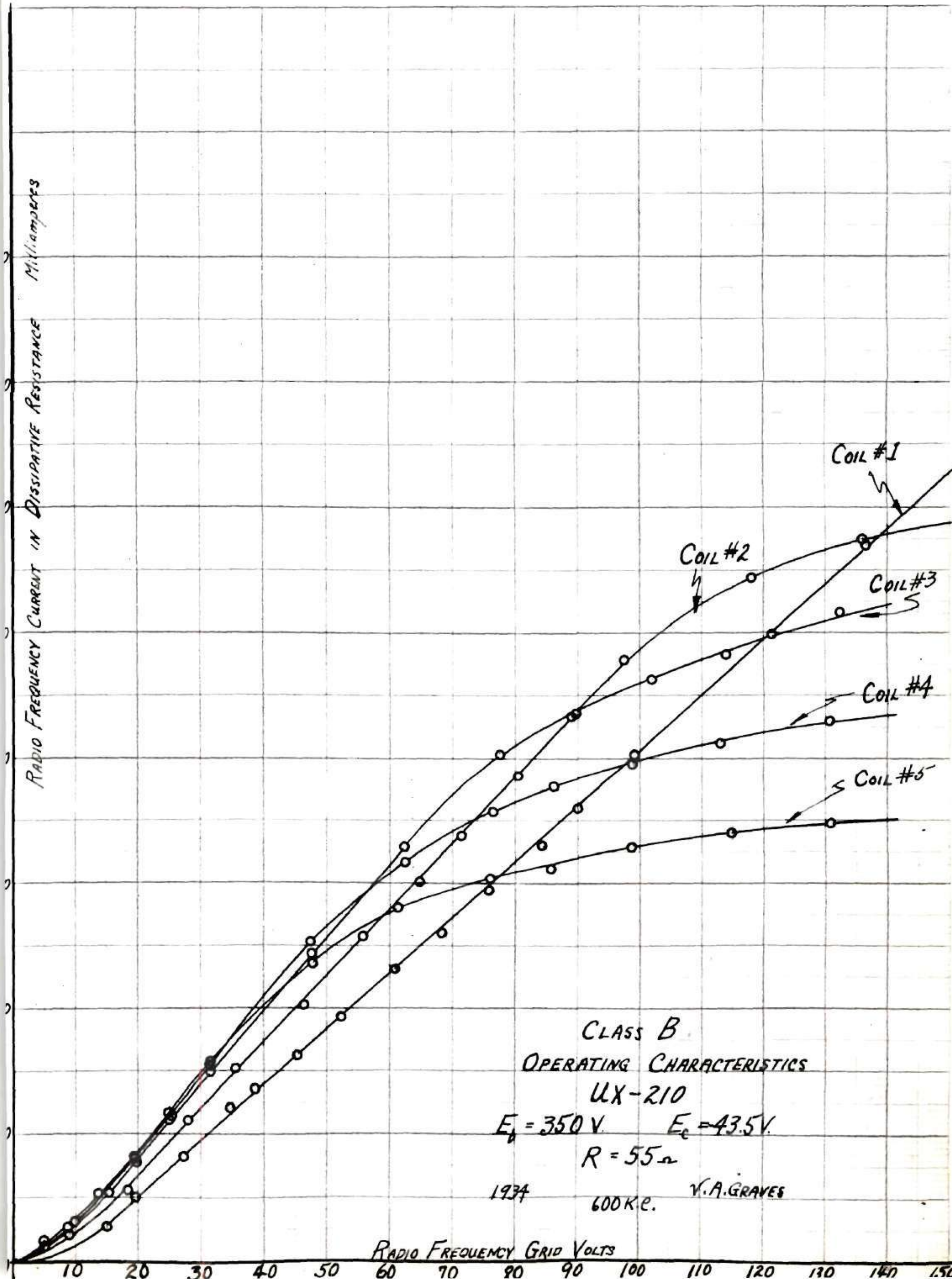
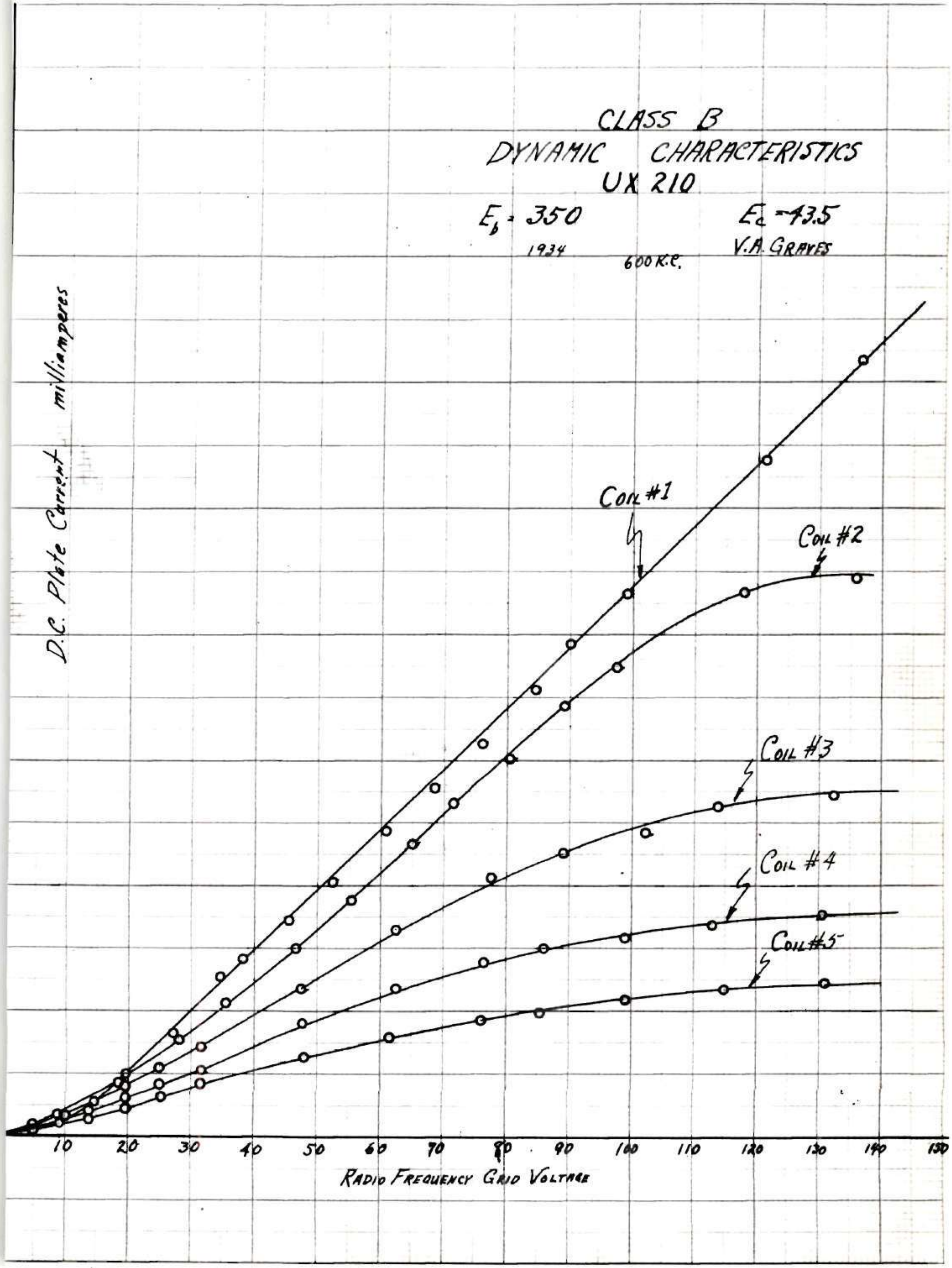

Radio Frequency Current in Dissipative Resistance Milliamperes
Coil #1
Coil #2
Coil #3
Coil #4
Coil #5
Class B
Operating Characteristics
UX-210
E_b = 350 V. E_c = 43.5 V.
R = 55 Ω
1934
600 Kc.
V. A. Graves
Radio Frequency Grid Volts
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150

Fig 12

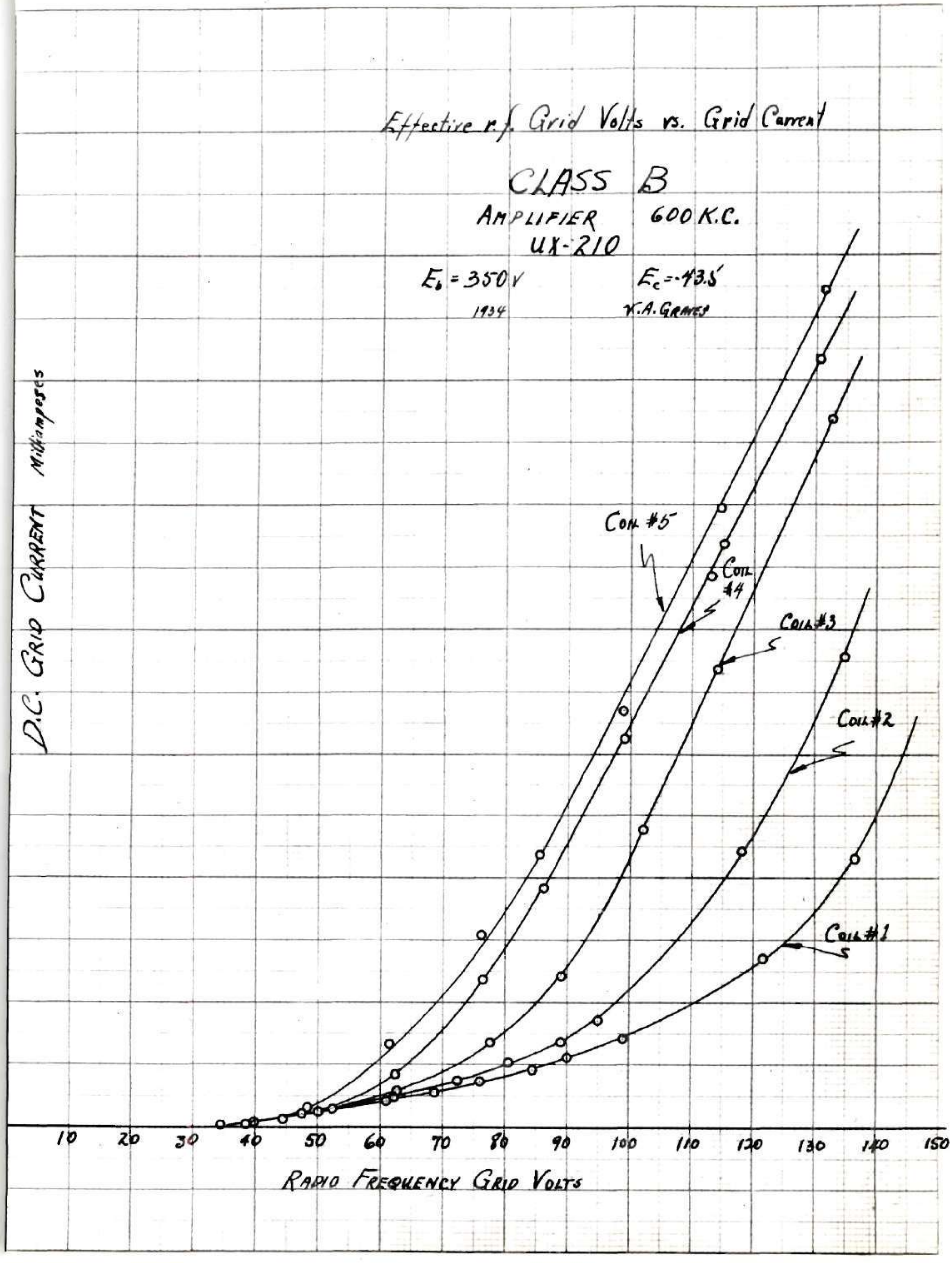

CLASS B
DYNAMIC CHARACTERISTICS
UX 210
E_b = 350
E_c = -43.5
1934
600 K.C.
V.A. GRAVES
D.C. Plate Current milliamperes
Coil #1
Coil #2
Coil #3
Coil #4
Coil #5
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
Radio Frequency Grid Voltage

UPPER LIMIT, THEN THE DRIVING VOLTAGE FOR LOAD #5 MUST NOT BE OVER 73 VOLTS. LIKEWISE FOR LOAD #1 THE VOLTAGE APPLIED TO THE GRID SHOULD NOT EXCEED 119 VOLTS, ELSE THE GRID CURRENT WILL BE GREATER THAN 10 MILLIAMPERES.

A STUDY OF FIGURES 3 AND 13 SHOWS THAT FOR POSITIVE GRID VILTAGE THE GRID CURRENT IS GREATER WHEN THE PLATE VOLTAGE IS SMALL RATHER THAN WHEN THE PLATE VOLTAGE IS HIGH. THE SWING OF THE INSTANTANEOUS PLATE VOLTAGE IS GREATER FOR THE HIGH IMPEDANCE LOADS THAN FOR THE SMALLER ONES AND THUS THE PLATE VOLTAGE REACHES LOWER VALUES WHEN THE HIGHER LOADS ARE USED. THIS LOW PLATE VOLTAGE CAUSES THE GRID CURRENT TO BECOME VERY LARGE, WHICH POSSIBLY INTRODUCES OBJECTIONABLE WAVE SHAPE DISTORTION AND EXCESSIVE DRAIN ON THE DRIVING STAGE SUPPLYING THE GRID VOLTAGE.

TABLES LISTING THE EXPERIMENTAL RESULTS FOLLOW:

Fig 13


Effective r.f. Grid Volts vs. Grid Current
CLASS B
AMPLIFIER 600 K.C.
UX-210
$E_b = 350V$
$E_c = -43.5$
1934
V.A. GRAVES
D.C. GRID CURRENT Milliamperes
COIL #5
COIL #4
COIL #3
COIL #2
COIL #1
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
RADIO FREQUENCY GRID VOLTS

EXPERIMENTAL DATA AS RECORDED WILL BE GIVEN:

COIL #1 OR LOAD # 1

GRID VOLTAGE (EFF.)	TANK CURRENT MA. (EFF.)	PLATE CURRENT MA. D.C.	GRID CURRENT MA. D.C.
15.0	28.5	5.8	0
19.5	52.0	10.0	0
27.5	83.5	16.5	0
34.5	122.3	25.6	.1
38.5	136.0	28.1	.25
45.5	164.8	34.4	.625
52.5	194.0	40.2	1.125
61.0	232.0	48.75	1.75
68.5	259.0	55.6	2.25
76.0	294.5	62.6	2.98
84.5	330.0	71.2	3.75
90.0	362.5	78.7	4.50
99.0	406.0	86.9	5.75
121.5	495.5	107.5	10.95
136.5	571.0	123.9	17.25

COIL #2 OR LOAD #2

GRID VOLTAGE (EFF.)	TANK CURRENT MA. (EFF.)	PLATE CURRENT MA. D.C.	GRID CURRENT MA. D.C.
9.0	21.5	3.75	0
18.5	57.7	8.75	0
28.0	110.0	15.61	0
35.5	152.5	21.2	0
46.5	201.5	30.0	.4
55.5	257.5	37.75	.7
65.0	300.0	46.9	2.1
71.5	337.0	53.1	2.4
80.5	385.0	60.0	4.0
89.0	433.0	68.7	5.7
97.5	480.0	74.45	8.0
118.0	544.0	86.9	17.75
136.0	572.0	88.7	30.5

COIL #3 OR LOAD #3

GRID VOLTAGE (EFF.)	TANK CURRENT MA. (EFF.)	PLATE CURRENT MA. D.C.	GRID CURRENT MA. D.C.
5.0	14.4	1.975	0
10.0	30.0	3.025	0
15.5	53.5	5.5	0
19.5	79.0	8.05	0
25.0	111.0	11.11	0
31.5	150.0	14.61	0
47.5	244.0	23.5	.775
62.5	328.0	33.0	2.22
77.5	405.0	41.5	5.5
89.0	431.0	45.0	9.75
102.0	464.0	48.2	19.1
114.0	480.0	52.7	29.5
132.5	520.0	54.4	45.5

COIL #4 OF LOAD #4

GRID VOLTAGE (EFF.)	TANK CURRENT MA. (EFF.)	PLATE CURRENT MA. D.C.	GRID CURRENT MA. D.C.
5.0	16.0	1.75	0
9.0	30.5	2.54	0
14.0	55.0	4.49	0
19.5	80.5	6.25	0
25.0	114.5	8.475	0
31.5	153.5	10.79	0
47.8	254.0	18.25	.8
62.5	317.0	23.9	3.25
76.5	357.5	27.8	9.5
86.0	378.0	30.0	15.5
99.0	395.0	32.0	25.0
113.0	413.0	33.75	35.5
130.5	432.0	35.7	49.5

COIL #5 OR LOAD #5

GRID VOLTAGE (EFF.)	TANK CURRENT MA. (EFF.)	PLATE CURRENT MA. D.C.	GRID CURRENT MA. D.C.
5.0	17.6	1.675	0
9.0	31.0	2.25	0
13.9	54.9	3.5	0
19.5	80.0	4.62	0
25.0	117.5	6.73	0
31.5	156.0	8.3	0
48.0	236.5	12.89	.95
61.5	283.0	16.0	5.75
76.0	304.0	18.71	12.48
85.5	312.0	19.85	17.6
99.0	330.0	21.75	26.8
115.0	341.0	23.5	37.7
131.0	348.0	25.0	53.7

EFFICIENCY

COIL #1

GRID VOLTAGE (EFF.)	OUTPUT WATTS	INPUT WATTS	EFFICIENCY %
15.0	.044	2.03	2.2
19.5	.148	3.5	4.25
27.5	.383	5.78	6.63
34.5	.823	8.95	9.2
38.5	1.015	9.84	10.33
45.5	1.493	12.05	12.4
52.5	2.07	14.1	14.7
61.0	2.96	17.4	17.02
68.5	3.69	19.5	18.9
76.0	5.77	21.9	21.8
84.5	6.00	24.9	24.1
90.0	7.225	27.55	26.22
99.0	9.0	30.4	28.82
121.5	13.55	37.6	36.0
136.5	17.95	43.4	41.2

EFFICIENCY

COIL #2

GRID VOLTAGE (EFF.)	OUTPUT WATTS	INPUT WATTS	EFFICIENCY %
9.0	.0254	1.312	1.94
18.5	.183	3.0	6.00
28.0	.666	5.4	12.18
35.5	1.28	7.42	17.25
46.5	2.235	10.5	21.25
55.5	3.5	13.2	27.65
65.0	4.95	16.4	30.2
71.5	6.25	18.6	33.6
80.5	8.15	21.0	38.8
89.0	10.33	24.0	43.0
97.5	12.68	26.0	48.75
118.0	16.25	30.4	53.5
136.0	18.0	31.0	58.0

EFFICIENCY

COIL #3

GRID VOLTAGE (EFF.)	OUTPUT WATTS	INPUT WATTS	EFFICIENCY %
5.0	.0114	.691	1.65
10.0	.0515	1.06	4.86
15.5	.1575	1.925	8.18
19.5	.343	2.82	12.15
25.0	.676	3.89	17.4
31.5	1.239	5.12	24.2
47.5	3.27	8.24	39.7
62.5	5.91	11.55	51.2
77.5	9.03	14.52	62.1
89.0	10.21	15.75	64.8
102.0	11.84	16.85	70.25
114.0	12.69	18.45	68.7
132.5	14.9	19.05	78.0

EFFICIENCY

COIL #4

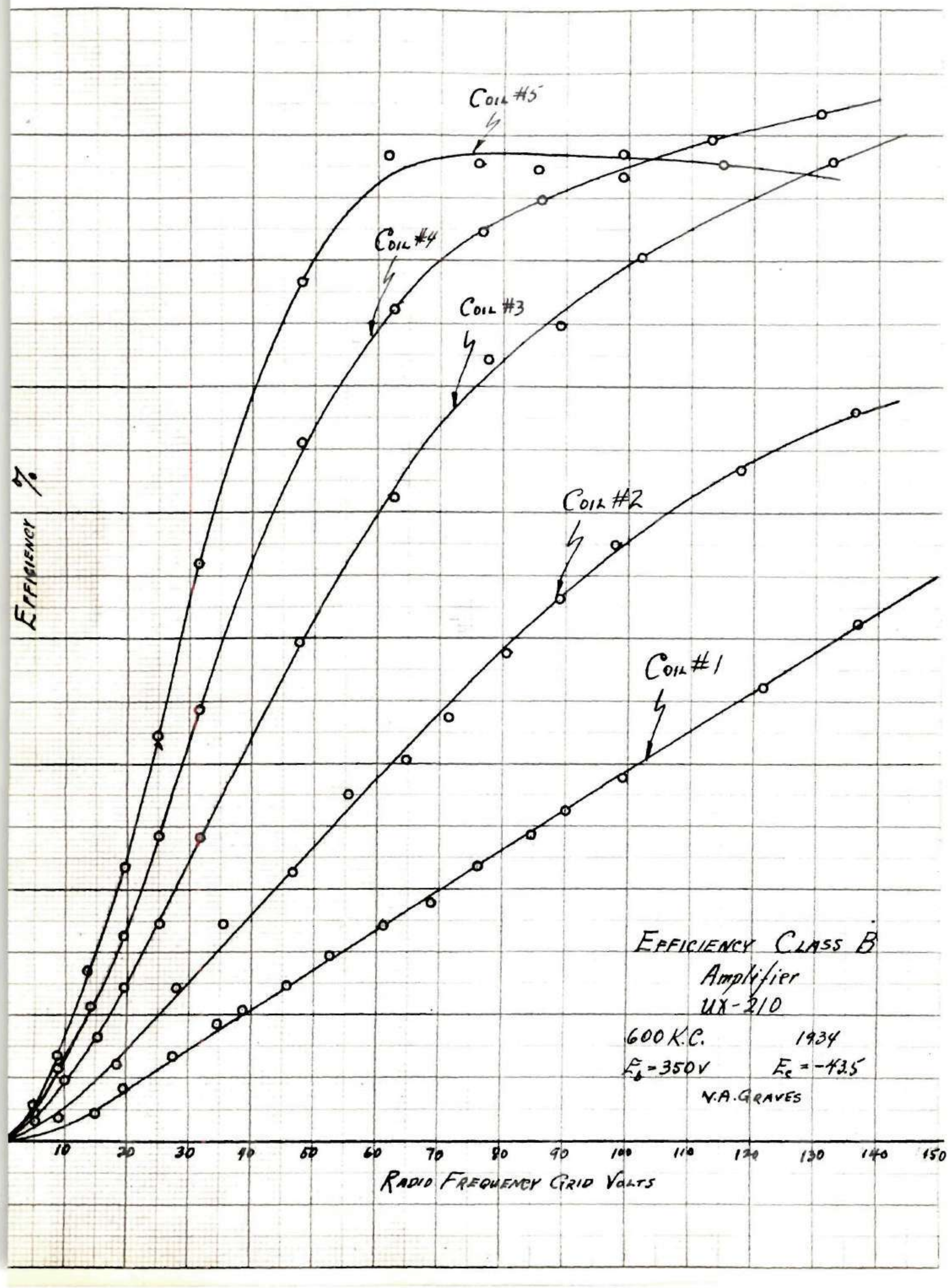
GRID VOLTAGE (EFF.)	OUTPUT WATTS	INPUT WATTS	EFFICIENCY %
5.0	.0141	.612	2.3
9.0	.051	.89	5.75
14.0	.1665	1.57	10.6
19.5	.35	2.19	16.25
25.0	.721	2.9	24.4
31.5	1.299	3.7	34.4
47.8	3.55	6.39	55.5
62.5	5.53	8.3	66.0
76.5	7.02	9.73	72.2
86.0	7.8	10.5	74.9
99.0	8.59	11.2	76.6
113.0	9.4	11.8	79.6
130.5	10.29	12.5	82.2

Efficiency

Coil #5

Grid Voltage (Eff.)	Output Watts	Input Watts	Efficiency %
5.0	.01705	.586	2.91
9.0	.096	.789	12.18
13.9	.1655	1.225	13.52
19.5	.352	1.62	21.75
25.0	.76	2.355	32.25
31.5	1.34	2.905	46.0
48.0	3.08	4.51	68.4
61.5	4.4	5.6	78.5
76.0	5.08	6.55	77.7
85.5	5.35	6.95	77.1
99.0	6.00	7.61	78.6
115.0	6.4	8.24	77.7
131.0	6.66	8.75	70.1

Fig 14


Coil #5
Coil #4
Coil #3
Coil #2
Coil #1
Efficiency %
10 20 30 40 50 60 70 80 90 100 110 120 130 140 150
Radio Frequency Grid Volts
Efficiency Class B
Amplifier
UX-210
600 K.C. 1934
E_b = 350V E_c = -43.5
V.A. Graves

SYNOPSIS AND DISCUSSION

THE EFFICIENCY CURVES SHOW THAT THE BEST OPERATING CONDITIONS ARE OBTAINED WHEN THE GRID VOLTAGE IS RELATIVELY HIGH AND THAT FOR CERTAIN LOADS THE EFFICIENCY IS DIRECTLY PROPORTIONAL TO THE DRIVING GRID VOLTAGE. THIS TEST WAS CONDUCTED WITH ONLY ONE VALUE OF GRID BIAS. HOWEVER, THE RESULTS WOULD BE SIMILAR REGARDLESS OF THE VALUE OF GRID BIAS USED. A HIGHER VALUE OF GRID BIAS WOULD ALLOW THE DRIVING VOLTAGE TO BE INCREASED WITHOUT AN EXCESSIVE CURRENT.FLOWING. THE MAXIMUM EFFICIENCY WOULD BE NEARLY THE SAME REGARDLESS OF THE GRID BIAS. THE THEORETICAL CALCULATIONS AND THE EXPERIMENTAL RESULTS CHECK TO A REMARKABLE DEGREE AS LONG AS THE MINIMUM PLATE VOLTAGE IS GREATER THAN THE MAXIMUM GRID VOLTAGE. THE THEORETICAL DISCUSSION HAS BEEN LIMITED TO DETERMINING EFFICIENCIES OF AMPLIFIERS YET THE SAME PROCEDURE WOULD BE FOLLOWED IN A STUDY OF DETECTION, DETECTION CONSTANTS, OSCILLATORS, AND MANY OTHER THEORETICAL APPLICATION OF VACUUM TUBES. THE WORK THAT HAS BEEN PRESENTED WAS ALONG THE LINE OF AN EMPIRICAL TREATISE TO WHICH CONCRETE EXPERIMENTAL DATA HAVE BEEN ADDED TO SUBSTANTIATE THE THEORETACAL METHODS.

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